Jet Propulsion Laboratory
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EXPERIMENTAL RESULTS OF SNOW AND SOIL MOISTURE MEASUREMENT FROM NON-VEGETATED AND VEGETATED SITES USING P-BAND SIGNALS OF OPPORTUNITY

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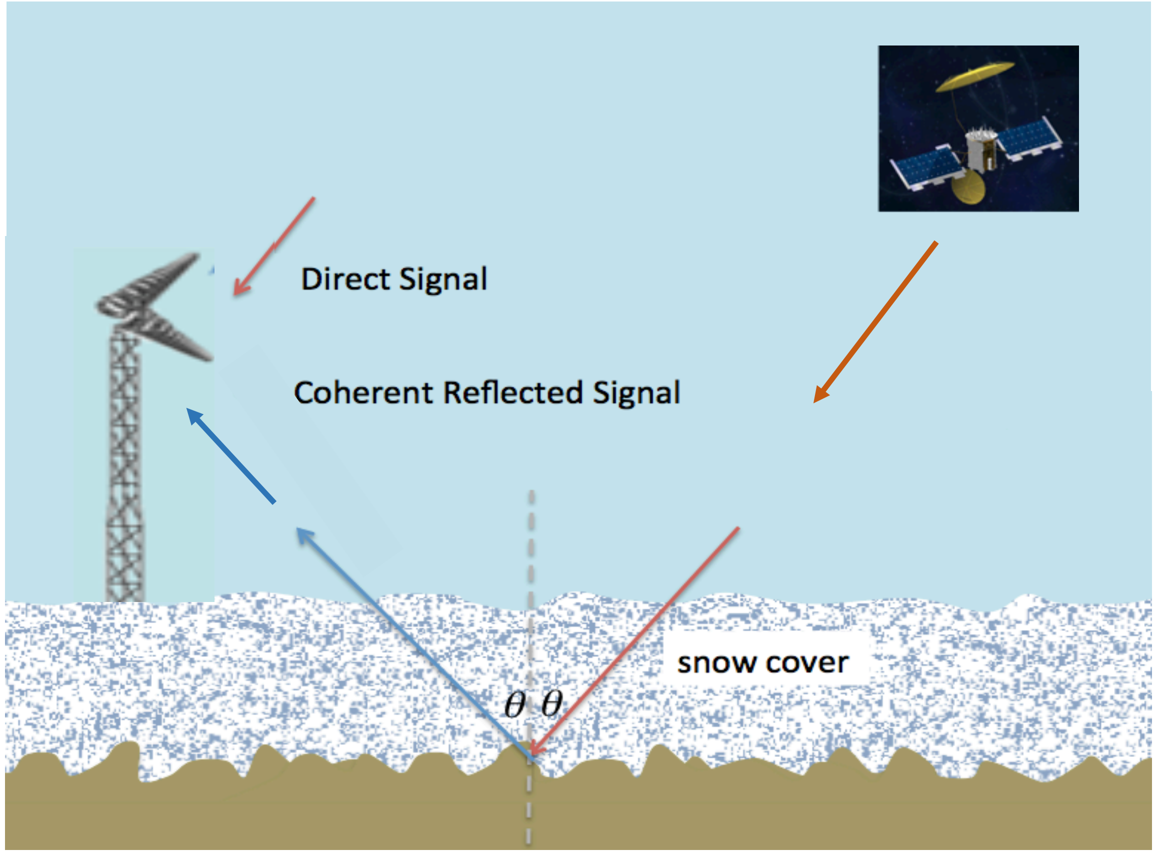
Overview

- Motivation
- Measurement Background
- Experiment Results
- OSSE Capability
- Summary

Motivation

- Snow water equivalent (SWE) and root zone soil moisture (RZSM) in land are critical state variables in the terrestrial water cycle with impact on weather, climate, and ecosystems
- Knowledge of SWE and RZSM are also critical for water supply management
- P-band Signals of Opportunity has greater penetration than L-band Sensors, such as SMAP and GNSS-R

Measurement Principle



$$R \simeq R(f, \boldsymbol{S}oil\ Moisture)$$
$$\phi_s \simeq \mathrm{a} \cdot f \cdot SWE$$

R = Reflectivity

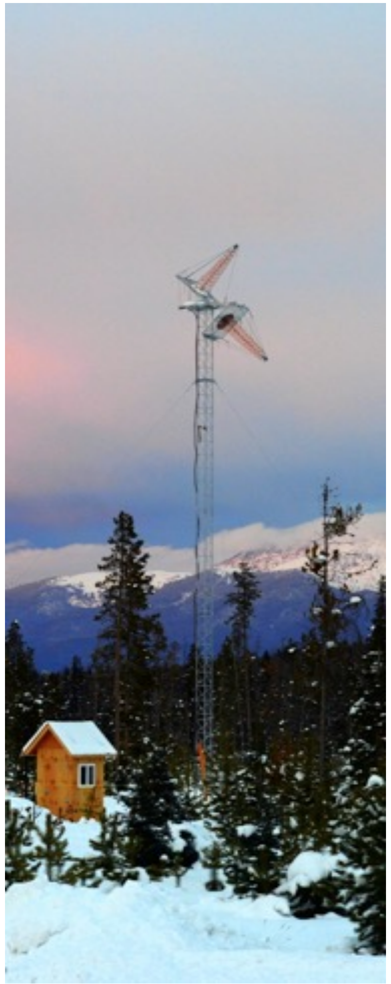
ϕ_s = phase change

f = frequency

a : depends on

incidence angle

Experimental Setup



Site A

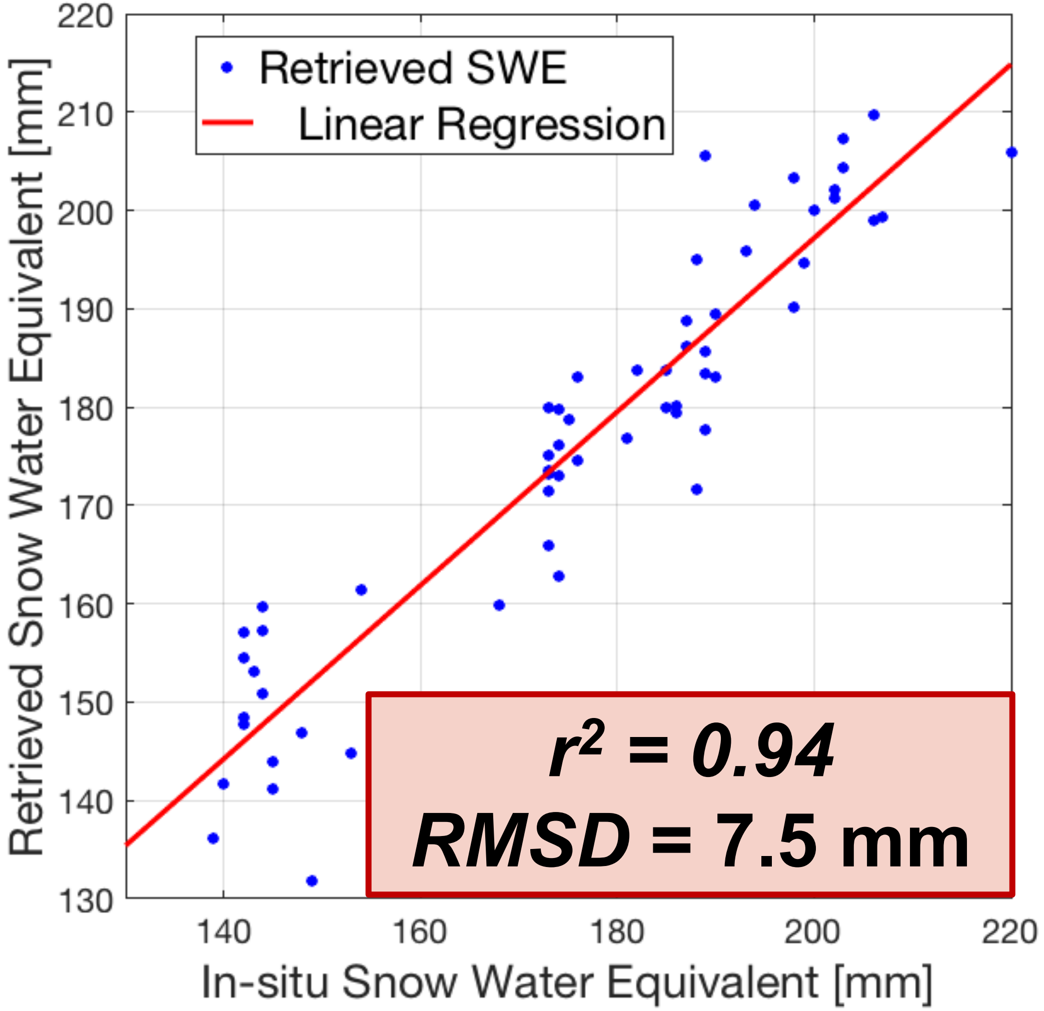
- Almost no vegetation
- Installed in Fall 2015
- Winter 2015-2016: 240-270 MHz
- Since 2016: 254-270 MHz, 360-376 MHz

Site B

- Has small trees
- Installed in Fall 2016
- Recording 254-270 MHz, 360-376 MHz

Fraser Experimental Forest

Winter 2015-2016: 260 MHz



$r^2 = 0.94$

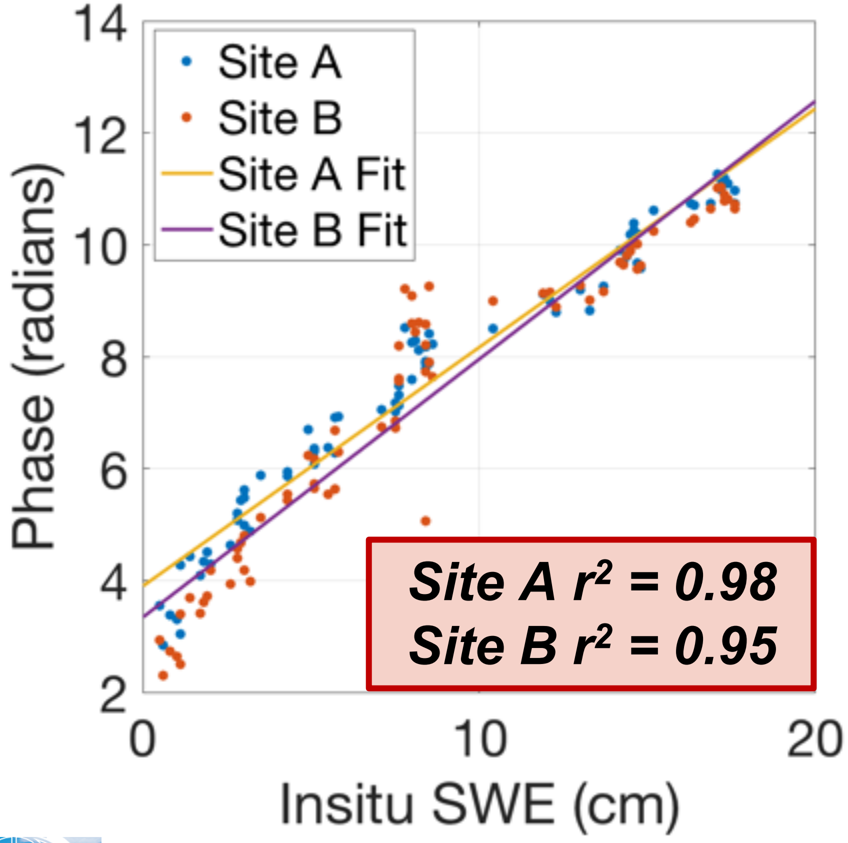
RMSD = 7.5 mm

Shah et al., 2017

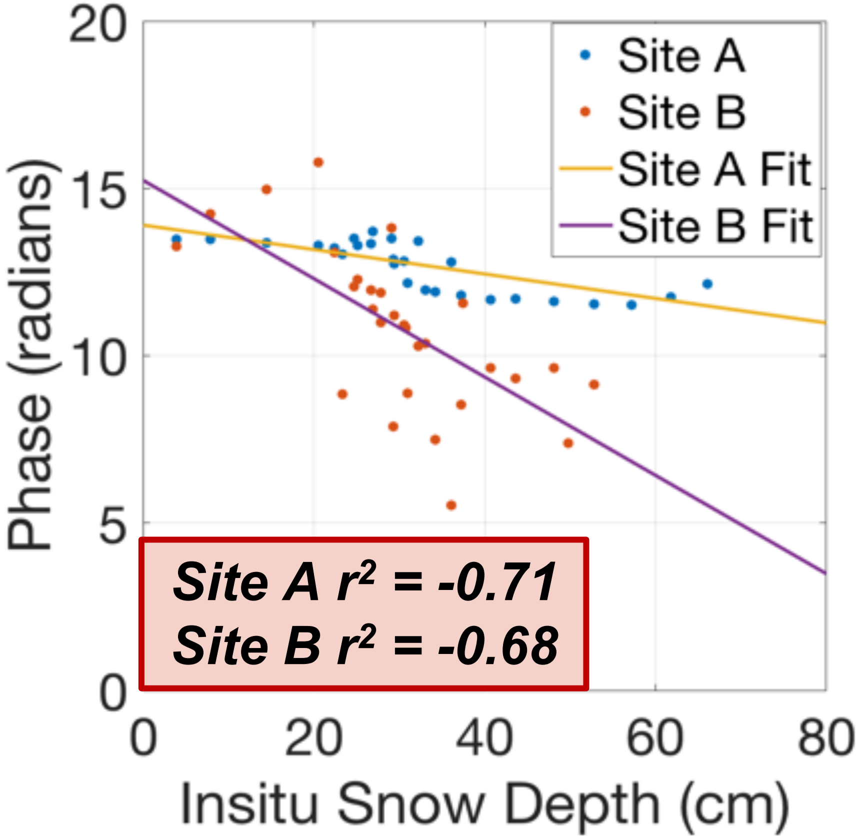
IGARSS 2019 7/23/19

Winter 2016-2017: 260 MHz

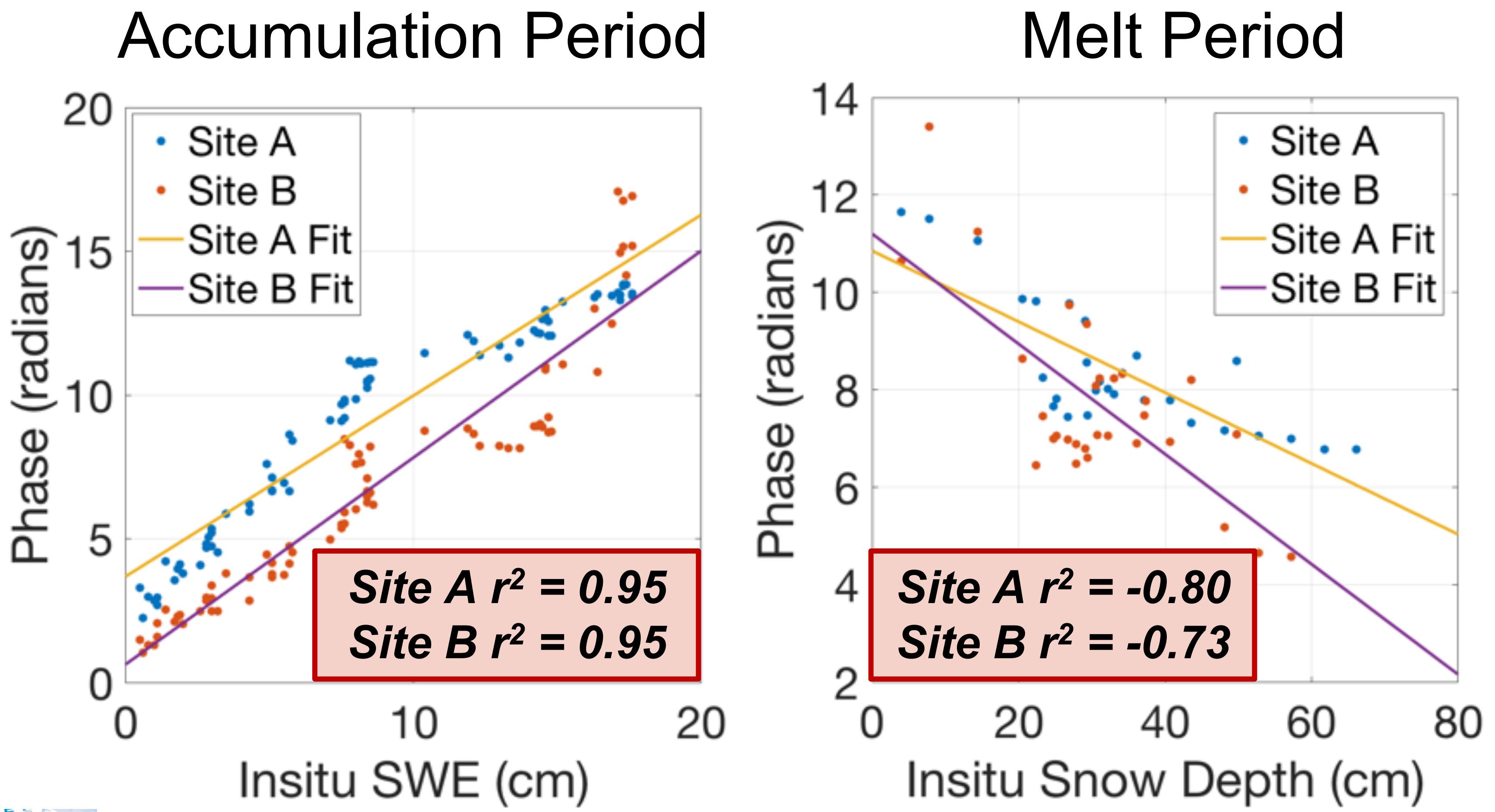
Accumulation Period



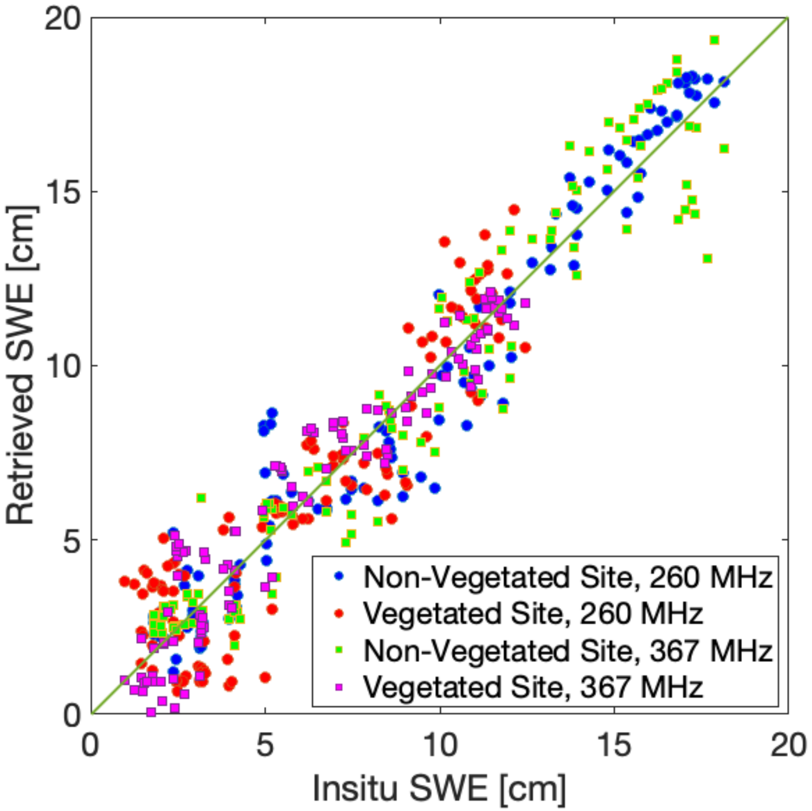
Melt Period



Winter 2016-2017: 367 MHz



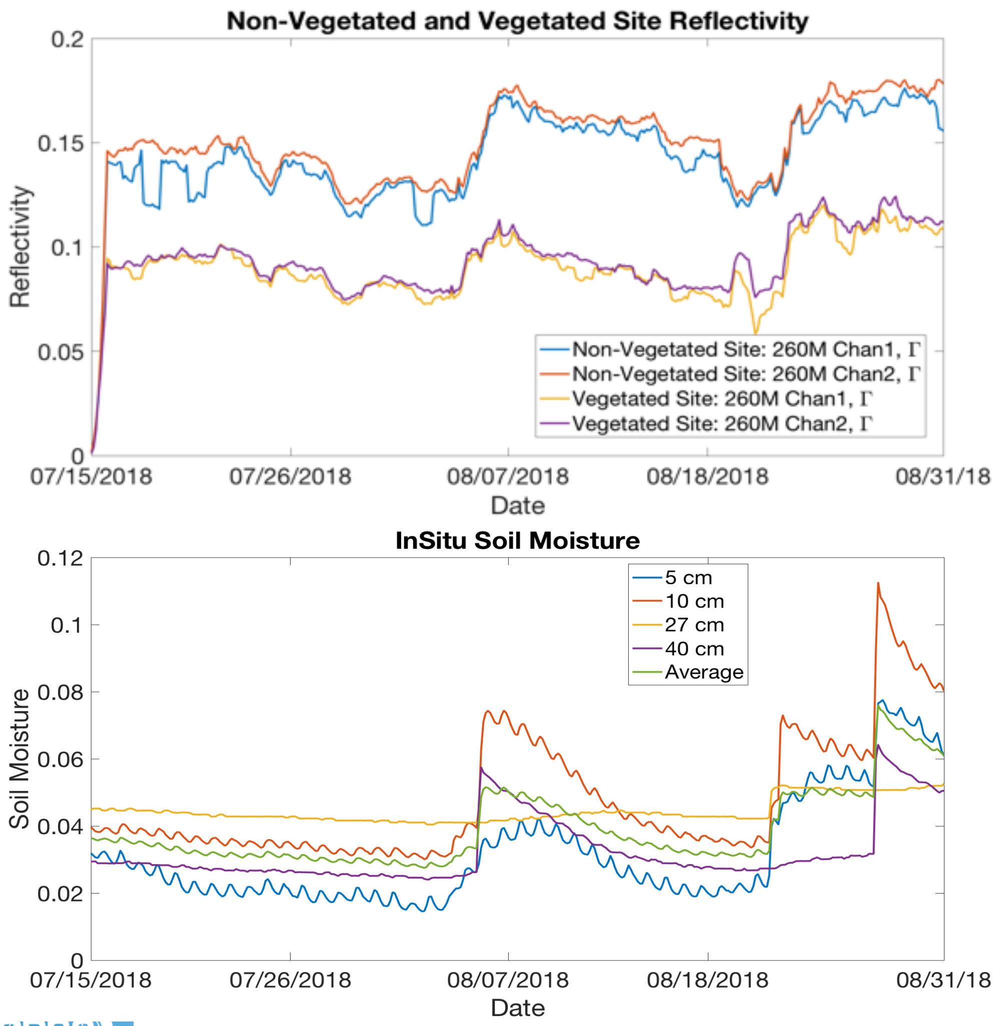
Winter 2017-2018



- Correlation were found to be more than 0.9 for all the frequencies.
- The RMSD between retrieved SWE and *in situ* SWE was found to be between 1.15-1.6 cm.

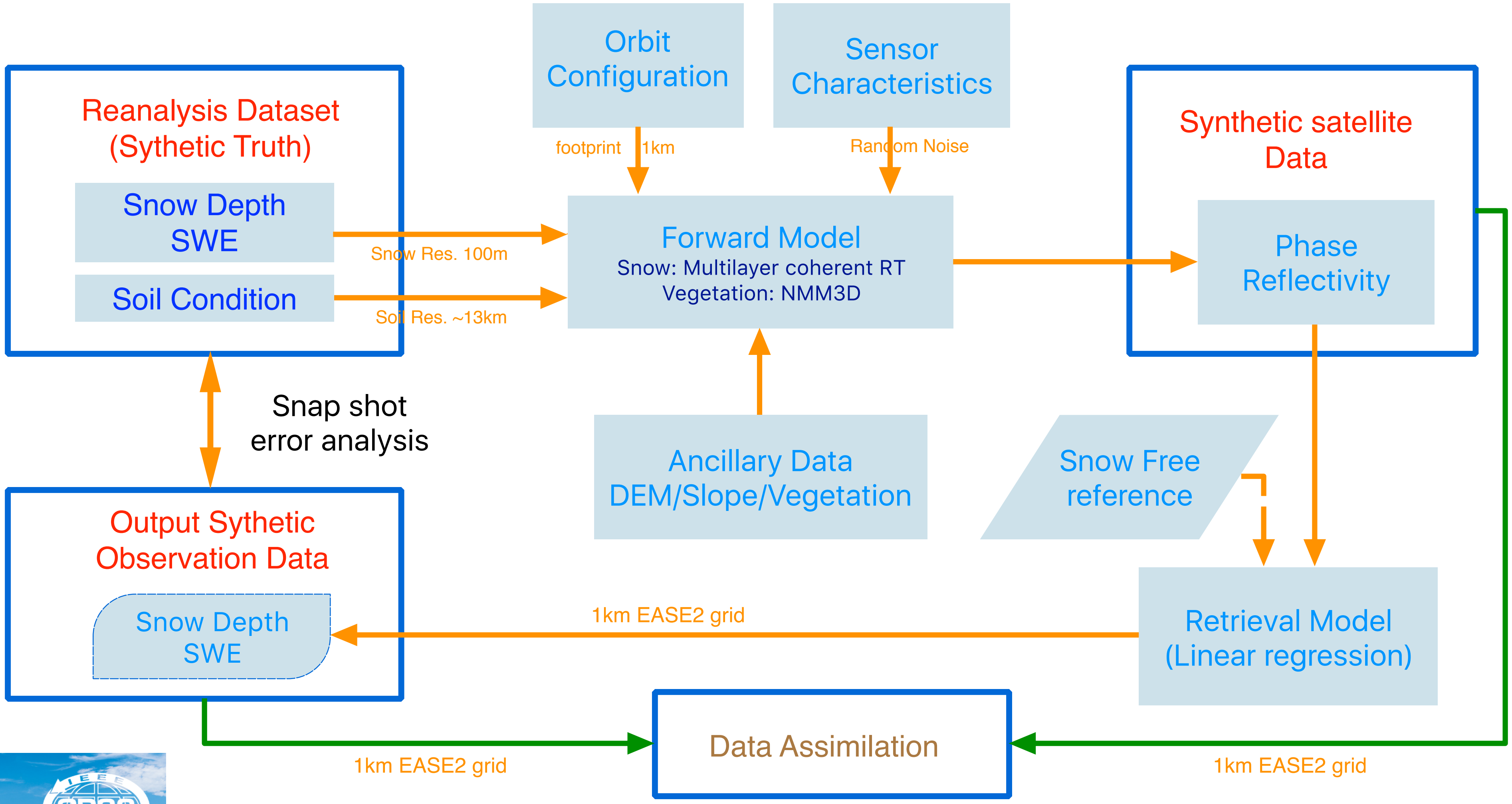
	260 MHz	370 MHz
Non-Vegetated Site	1.26 cm	1.50 cm
Vegetated Site	1.60 cm	1.15 cm

Summer 2018: Soil Moisture

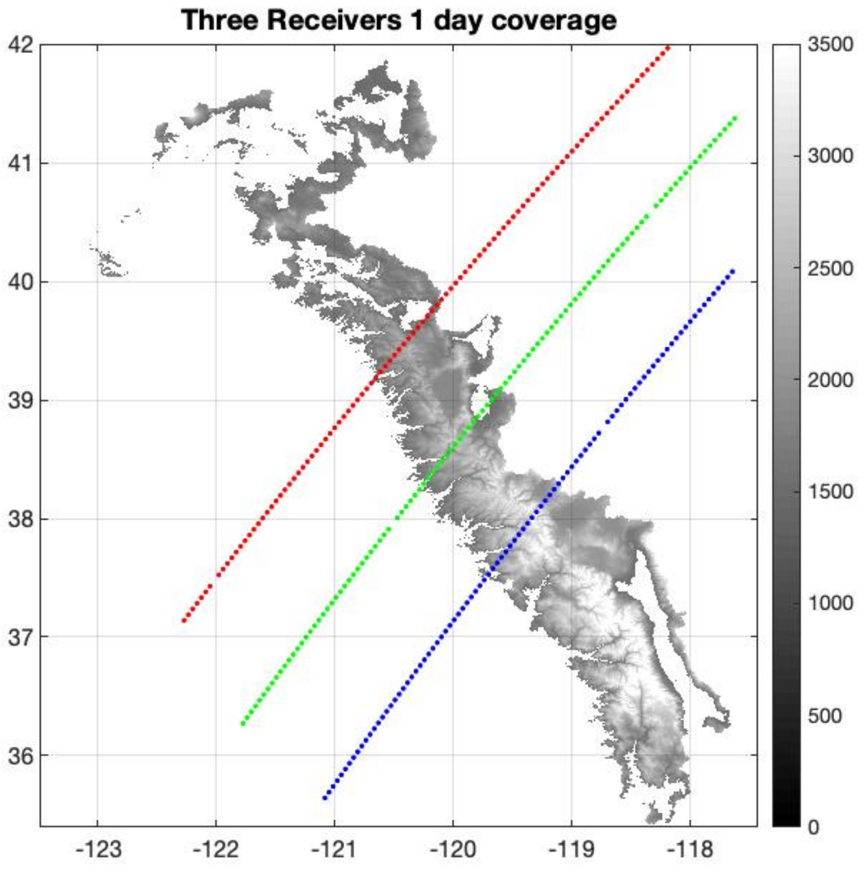


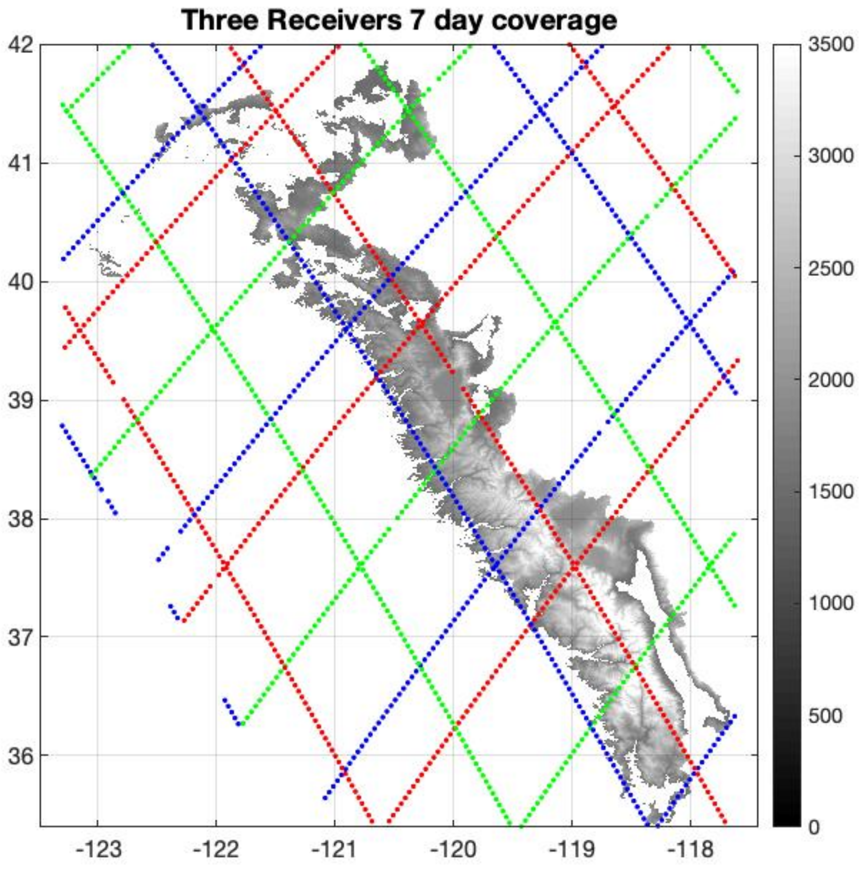
- Both sites showed sensitivity to the changes in soil moisture
- Correlation between reflectivity and soil moisture was between 0.6-0.7
- Attenuation due to vegetation is also observed as the reflectivity

OSSEs Capability Development



Coverage over east sierra

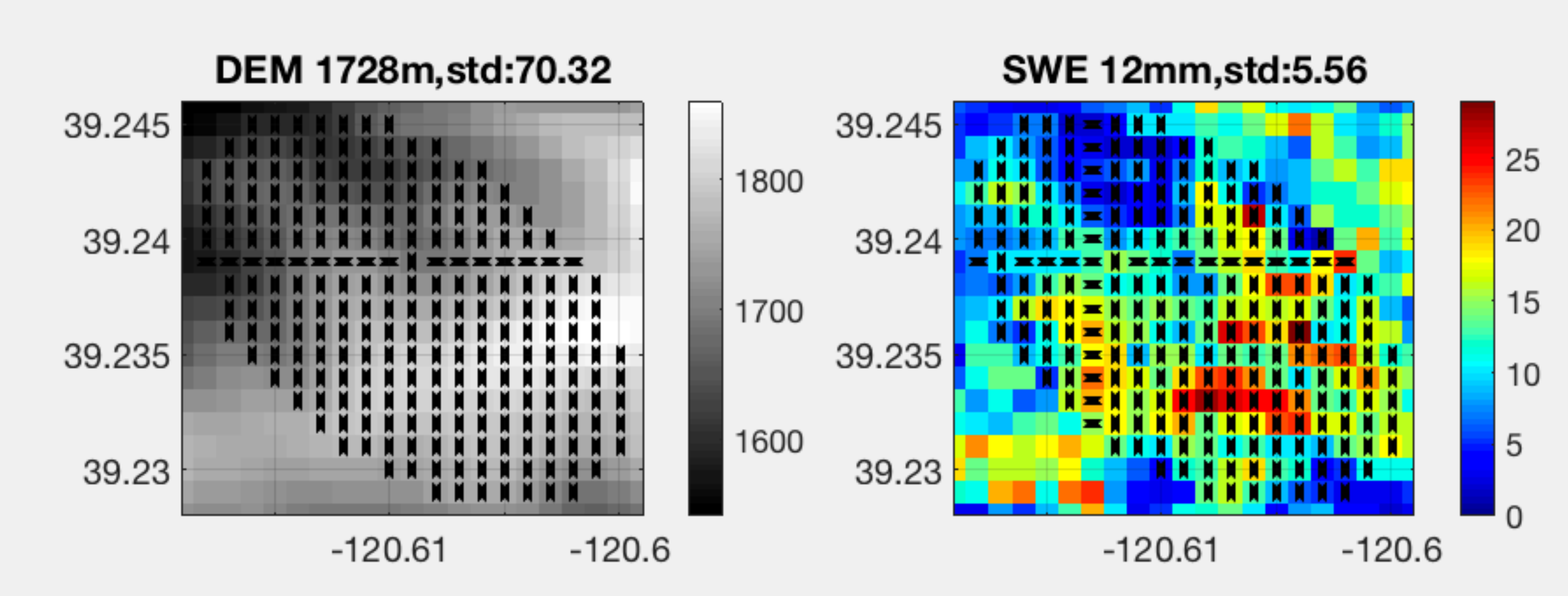




Case study: Inhomogeneity over footprint

- DEM effect
- SWE inhomogeneity

Black crosses mark the first Fresnel zone for MUOS transmitter and receiver at 475km over east sierra area. The foot print is about 1km, and subgrid is 100m



Numerical calculation using Kirchhoff integral

- Input data: DEM and SWE is in 100m.
- The scattered field is calculated using Kirchhoff integral '

$$\bar{E}_s(\bar{r}) = \frac{ik}{4\pi}\sqrt{\frac{P_t\eta_0}{2\pi}}\iint_{S'} d\bar{r}' \frac{e^{ik(R_{pt}+R_{pr})}}{R_{pt}R_{pr}}\left(\bar{\bar{I}} - \hat{k}_s\hat{k}_s\right)\cdot\bar{F}(\alpha,\beta)$$

$$\bar{F}(\alpha,\beta) = \sqrt{1+\alpha^2+\beta^2}\begin{bmatrix} (-1+R_h)\left(\hat{e}_i\cdot\hat{k}_i\right)\hat{q}_i + (1+R_v)(\hat{e}_i\cdot\hat{p}_i)\hat{n}\times\hat{q}_i \\ +\hat{k}_s\times[(1+R_h)(\hat{e}_i\cdot\hat{q}_i)]\hat{n}\times\hat{q}_i + (1-R_v)(\hat{e}_i\cdot\hat{p}_i)\left(\hat{n}_i\cdot\hat{k}_i\right)\hat{q}_i \end{bmatrix}$$

Where, the local orthonormal system is defined as followed,

$$\hat{q}_i = \frac{\hat{k}_i\times\hat{n}'}{\left|\hat{k}_i\times\hat{n}'\right|}$$

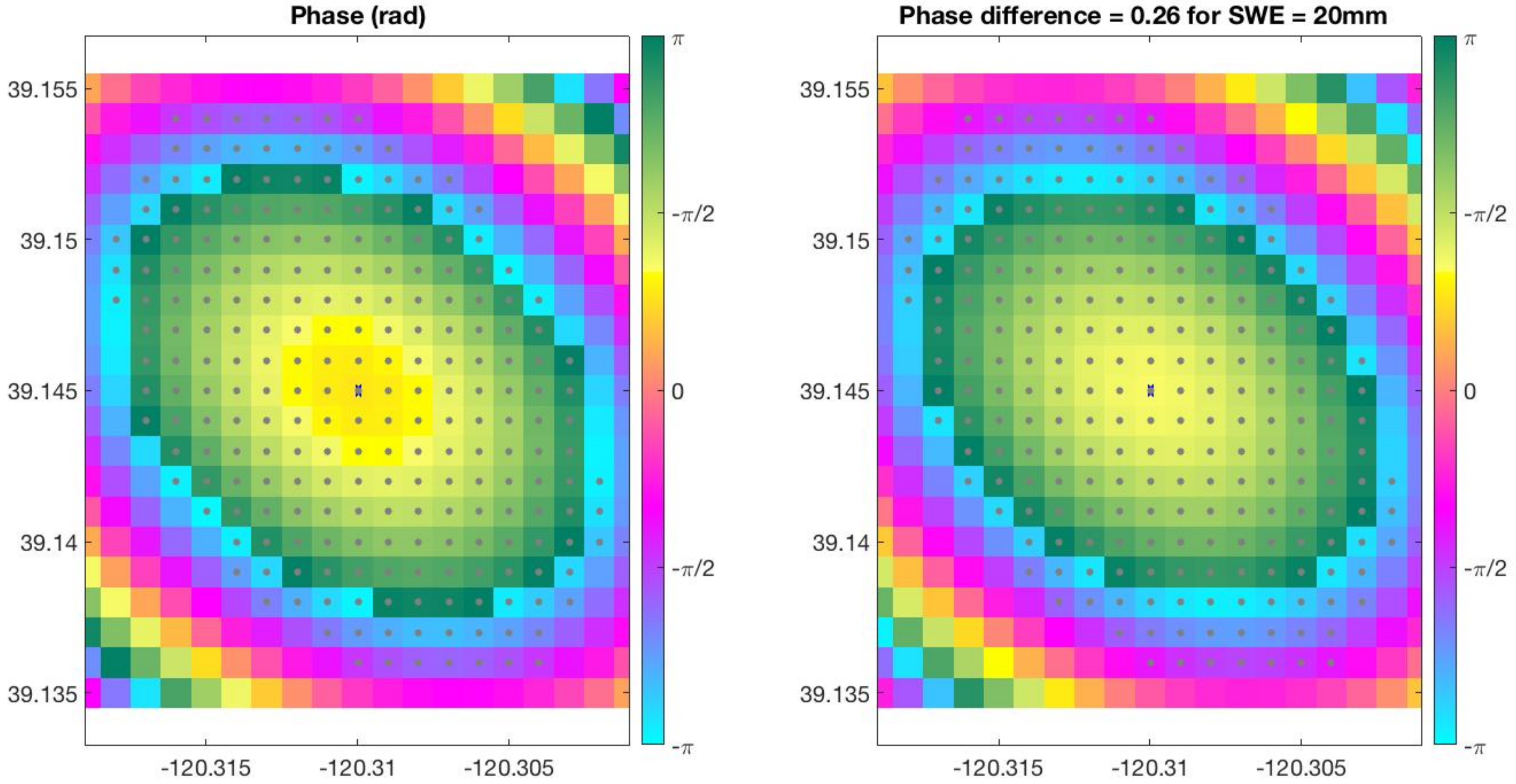
$$\hat{p}_i = \hat{q}_i\times\hat{k}_i$$

Alpha and beta are the local slopes of the horizontal direction (x,y)

W. Gu, H. Xu, and L. Tsang, "A Numerical Kirchhoff Simulator for GNSS-R Land Applications," *Progress In Electromagnetics Research*, Vol. 164, 119-133, 2019.

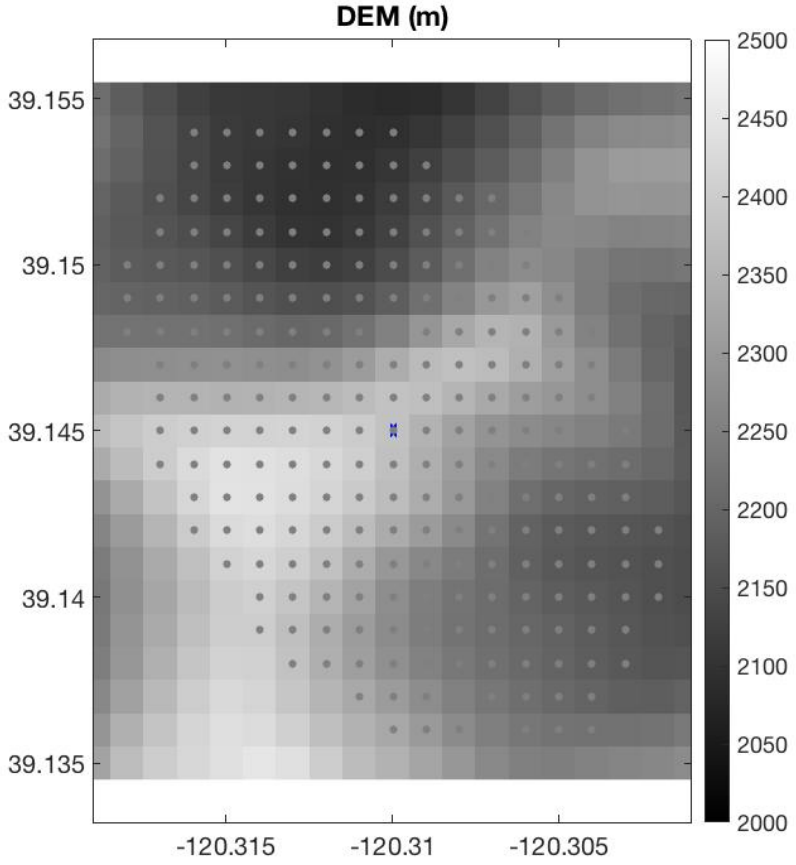
Ideal case: homogeneous SWE distribution on flat surface

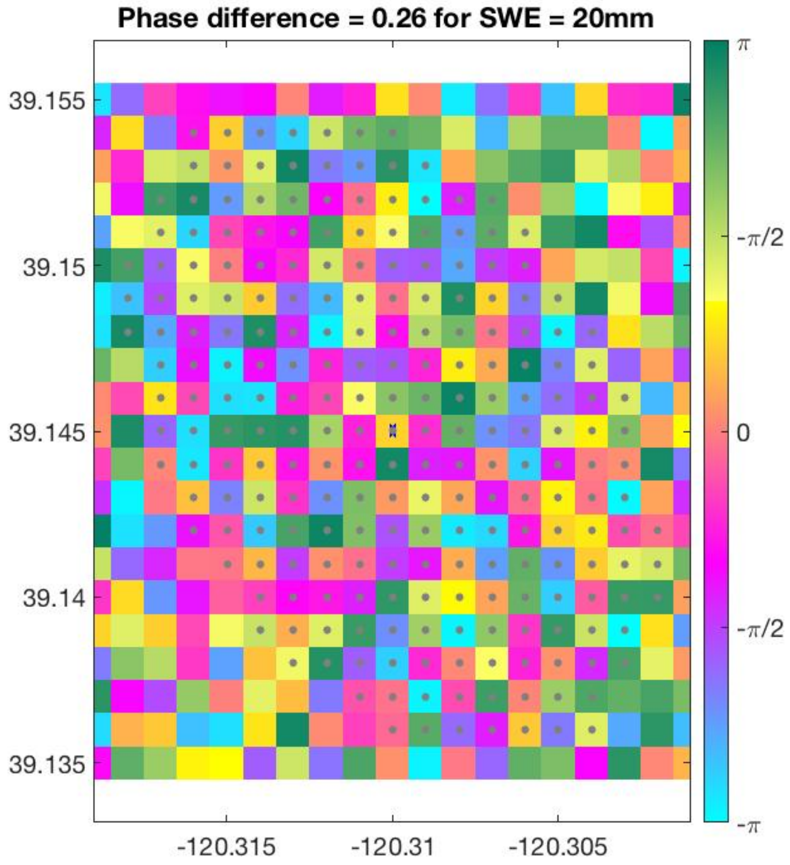
- Bare Surface



Phase difference
$\boldsymbol{\delta}$ = angle(Es_snow/Es)
Es and Es_snow is summation of the pixel in the first Fresnel zone

Case2: homogeneous SWE distribution with DEM





This footprint is from a mountain range with mean elevation of 2259m and std of 95m

Phase distribution is random due to DEM, however, the phase difference between snow on and off stays the same.

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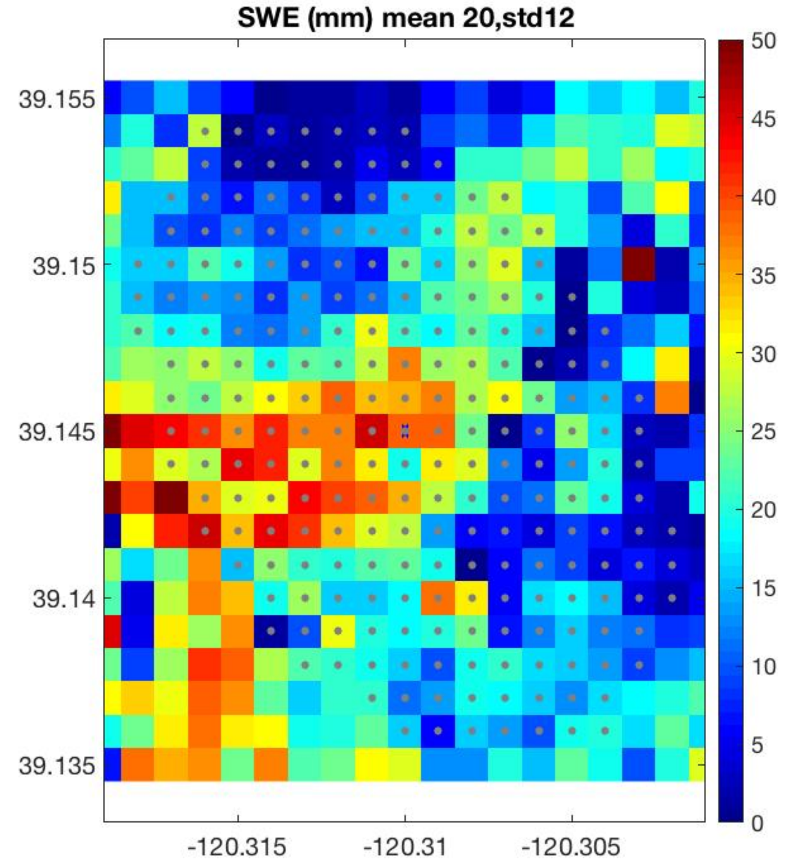
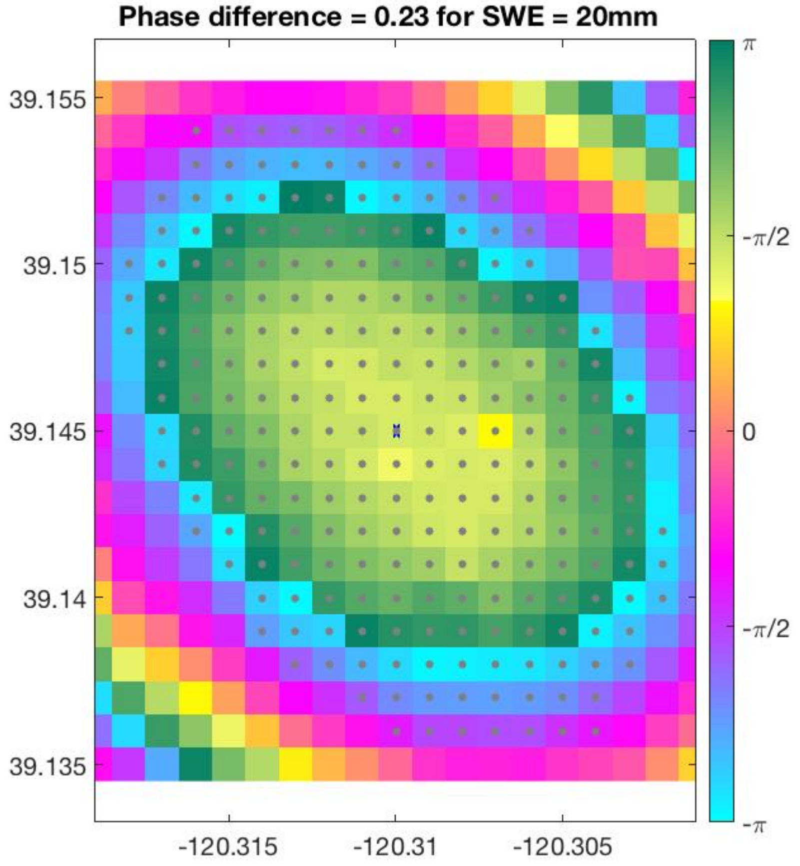
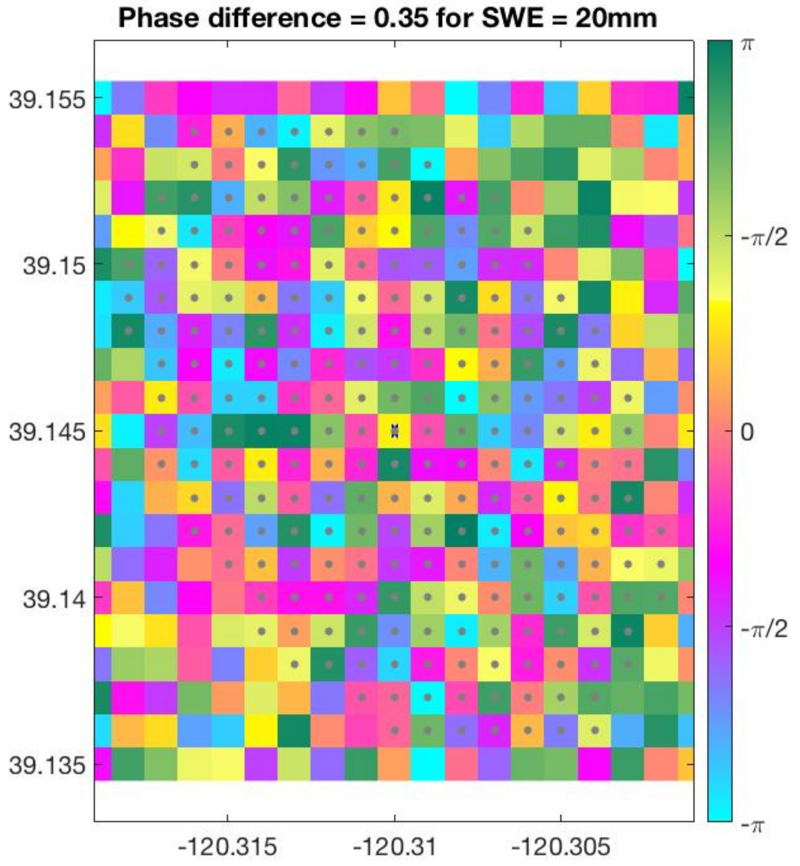
Case 3: real SWE distribution





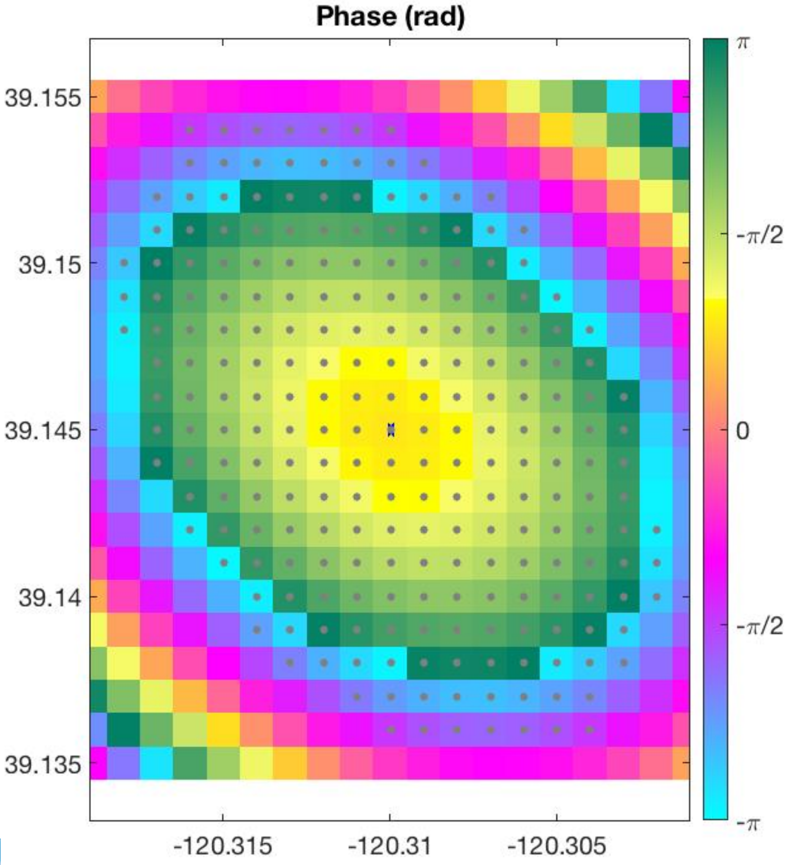
Real SWE distribution on flat surface

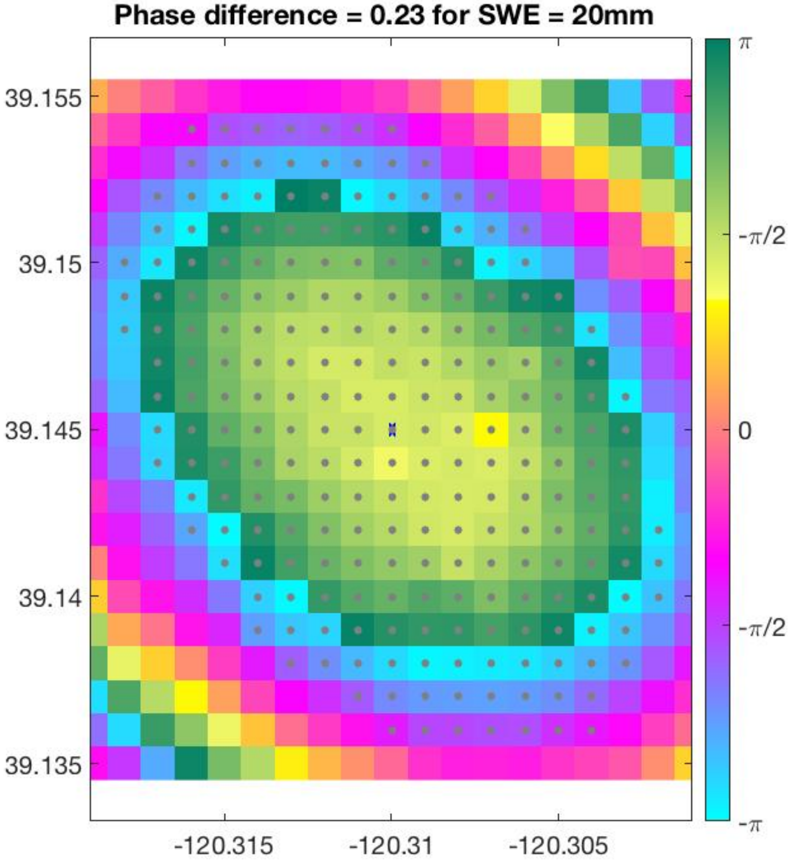


Real SWE distribution with DEM

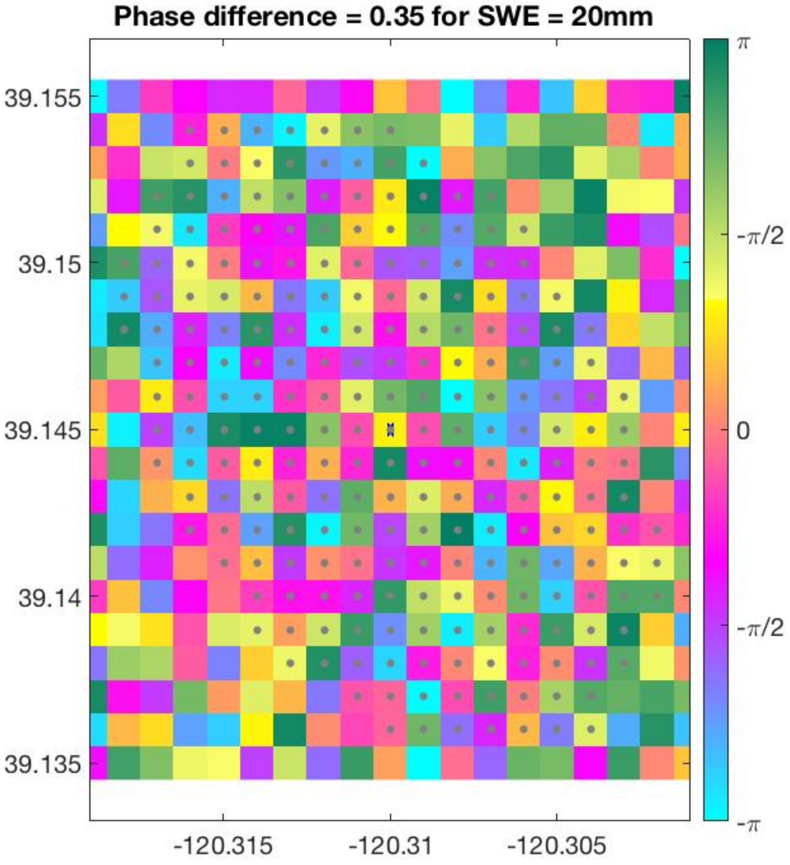
Phase map due to inhomogeneous SWE and DEM

Phase difference
δ = angle(Es_snow/Es)
Es and Es_snow is summation of the pixel in the first Fresnel zone





Real SWE distribution on flat surface



Real SWE distribution with DEM

Conclusion

- If the snow distribution over the first Fresnel zone is homogeneous, the DEM will destruct the phase distribution, but will not change the phase difference between the snow on and off scene. The SWE can be retrieved directly.
- If the snow is not distributed evenly over the first Fresnel zone, for the flat surface case, the phase difference is close to the mean snow case.
- If the snow is not evenly distributed in a rough terrain, there will be large uncertainty in the phase difference.

Summary

- SoOp technique can provide accurate sampling of SWE
- Phase directly proportional
  - SWE for dry snow
  - Snow Depth for wet snow
- Measurement principle demonstrated with field campaign
- Minimal effect of vegetation noticed for short trees
  - Measurement under canopy possible
- UAV Experiment will be done in future
- OSSE capability being built for end-to-end simulations
  - If the snow distribution over the first Fresnel zone is homogeneous, the DEM will destruct the phase distribution, but will not change the phase difference between the snow on and off scene. The SWE can be retrieved directly.